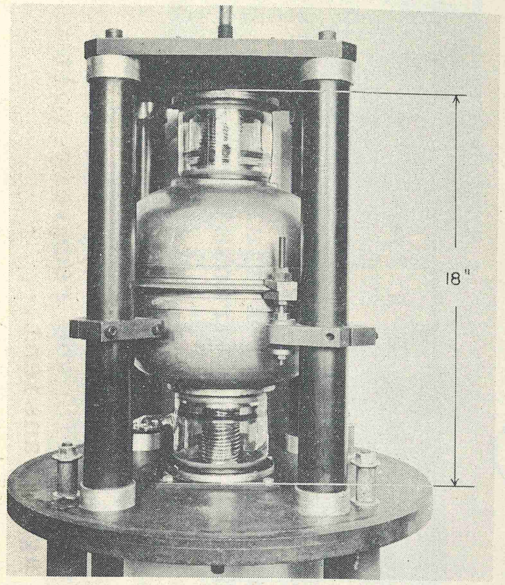

Fig. 6. Experimental high current vacuum interrupter. This device successfully interrupted 43,000A at 15.5 KV

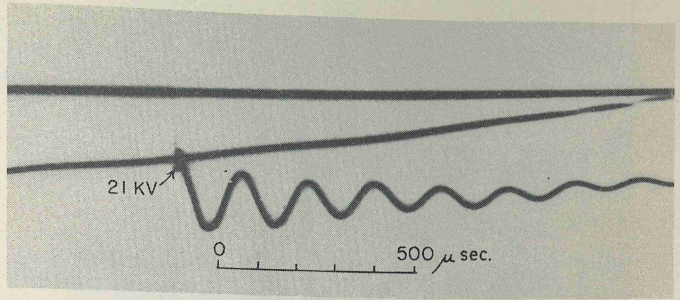

Fig. 7. Cathode ray oscillogram showing the successful withstanding of a recovery rate of 6KV/μsec by the interrupter illustrated in Fig. 3 after interrupting 27,000A at 18 KV.

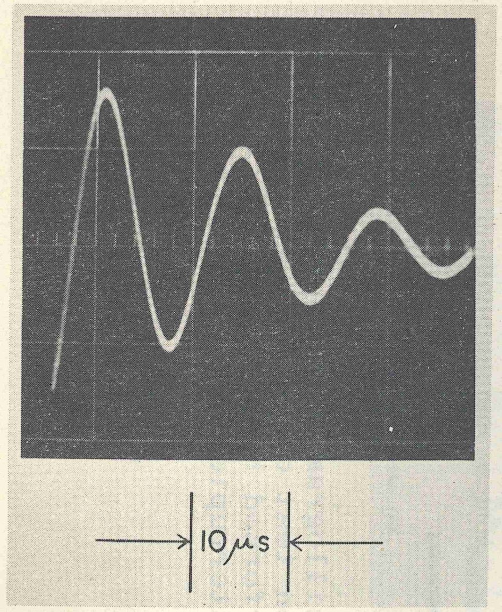

Fig. 8. Oscillogram showing the natural frequency of the circuit for the test recorded in Fig. 8. From this oscillogram it was calculated that the rate of rise of recovery voltage was 6KV/μsec.

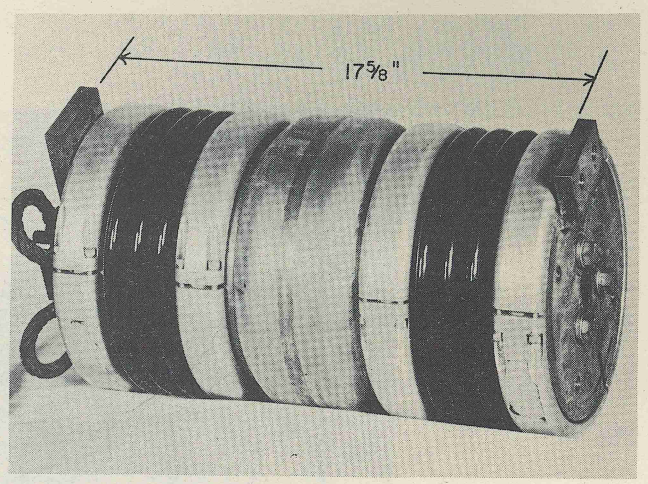

Fig. 9. Porcelain clad vacuum interrupter. This device successfully interrupted 40,000A at 15.5 KV. Two interrupters in series cleared 24,000A at 34.5KV.

Transactions Paper

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DEVELOPMENT OF POWER VACUUM INTERRUPTERS

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DEVELOPMENT OF POWER VACUUM INTERRUPTERS

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SUMMARY

The practicality of using vacuum interrupters for switchgear applications has been demonstrated by the successful development of a number of prototype devices. Interrupting tests have been made at currents up to 43000 A. at 15.5 KV and recovery rates up to 6000 V/μsec. This has been achieved by resolving many difficult technical problems, so that the vacuum interrupter now closely approaches the functional specification of an ideal interrupting device.

INTRODUCTION

Thirty five years ago, Sorensen disclosed[1] experiments made by him and his colleagues for the purpose of evaluating vacuum as a switching ambient for power circuit interrupters. Sorensen's work stimulated a great deal of interest in the Switchgear Industry. This is not surprising, because if the functional specification of an ideal circuit interrupter is formulated, a vacuum device comes closest to meeting this specification. Consider, for the moment, some of the ideal requirements. A good interrupter should effect rapid and quiet interruption; have long contact life, and be operated by a simple mechanism with no auxiliary equipment. It should also present no fire hazard and be insensitive to atmospheric ambient. All of these requirements are realizable in a vacuum interrupter. Why, then, has this potential not been exploited to any significant degree during the past three and a half decades? The answer is that there have been a number of very serious, very fundamental obstacles blocking the way of progress in vacuum interrupter technology. Until solutions had been found to these problems, no great strides could be made. Until very recently, commercially available vacuum interrupters were capable of interrupting only a few thousand amperes and were therefore restricted to load-break and capacitance-switching applications.

A few weeks ago, the first practical device using high current vacuum interrupters was announced by the company with which the authors are associated. This is the 560A heavy duty vacuum recloser described by Streater et al[2]. The introduction of this device represents the culmination of an extensive, concentrated research and development program. The purpose of this paper is to describe that part of the program devoted to the development of vacuum interrupters for power system applications. An historical survey has been written by Cobine[3], which includes much of the earlier work.

In order to determine the technical feasibility of using vacuum interrupters in switchgear applications, it must be shown that these devices can satisfy the functional specifications required by the applications. This calls for acceptable performance in the following important areas:

A) Current interrupting ability

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B) The current level at which the interrupter can close in without producing excessive welding and contact erosion. Coupled with this is a requirement for momentary current withstand ability.

C) Dielectric withstand capability at power frequency and under impulse conditions.

D) Insulation coordination with other components in the power system.

E) Ability in switching low inductive and capacitive currents without producing intolerable overvoltages.

F) Switch life, both under load and no-load conditions.

G) Continuous current carrying ability.

As the state of the art stood at the inception of this program, it appeared that to achieve satisfactory performance in all of these areas, characteristics were required in the components of the interrupter, which were seriously conflicting. This will become clearer as the paper proceeds.

HIGH CURRENT INTERRUPTION IN VACUUM

For both outdoor and indoor circuit breakers, a preferred list of interrupting ratings has been set down by A.S.A. standards[4]. Typical ratings are 8000, 12,500, 25,000 and 40,000 amperes. The experience of many investigators has repeatedly demonstrated the high intrinsic dielectric strength of vacuum gaps, but when attempts were made to rupture currents of the aforementioned magnitude in vacuum, the results were disappointing. No success in consistently interrupting high currents in vacuum has been reported in the literature. Commercially available vacuum switches have heretofore been able to break only a few thousand amperes. For these reasons a significant portion of the program was devoted to studying the factors which influence current interrupting ability in vacuum. These factors were first identified, isolated and studied by designed experiments and then the favorable factors were combined in designing prototype interrupters in order to attain the goal of high current interruption. Many experimental interrupters were built for this purpose. Four of these are shown and described in this paper.

Fig. 1 shows an interrupter that was continuously pumped. The envelope was made of alumina ceramic and the contacts were 3/4" cylindrical copper rods with a separation of 3/8". The object of this particular device was to study the effect of contact material on interrupting performance. At 15.5 KV this interrupter successfully cleared 5750 rms amperes, which is more than twice the symmetrical current that could be interrupted by tungsten contacts. Twelve tests were made at about the same level, and all were successful. It should also be pointed out that the arc was invariably interrupted at the first current zero. These results were very encouraging and significant for they represented a considerable improvement in performance over refractory contacts in otherwise identical conditions. Consequently refractory metal contacts were abandoned for high current interruption duties. These tests also gave some preliminary indication of the importance of a good condensing shield for metal vapor from the arc.

To improve the performance still further, the simple butt contacts were abandoned in favor of copper contacts in the form of discs which had spiral slots cut in them for the purpose of producing a magnetic field transverse to the arc[5]. Fig. 2 shows one of the interrupters used and a typical contact is shown in Fig. 3. When the arc spot is near the center, there exists a magnetic field due to the local current loop, which tends to drive the arc towards the periphery. On reaching the end of a petal, the arc establishes a new spot on the next adjacent petal and transfers to it. Thereupon, conditions are such that rotation continues. It is believed that the rotation of the arc has at least two advantages: (1) it distributes the energy input to the electrode over a larger area, thus facilitating more rapid cooling, and (2) it disperses the arc products over a larger area on the condensing shield. The condensing shield is metallic and is electrically isolated from both contacts[6]. The contact gap in this device was 1/2".

This interrupter successfully cleared 18,200 rms amperes at 16.5 KV. For some of the tests, air core reactors were intentionally placed in the circuit in close proximity to the interrupter, in order to increase the recovery rate imposed upon it. Fig. 4 shows a typical magnetic oscillogram taken during tests. Unless the contacts parted very shortly before a current zero, the arc always extinguished at the first current zero.

Besides clearing much higher currents than had been possible before in vacuum, this interrupter was characterized by extremely consistent operation and minimal contact erosion after a large number of tests. In this regard, the ASA specification[7] for the 560A heavy duty recloser can be taken as a bench mark. A duty cycle for such a recloser comprises an opening operation followed by three close-open operations. A total of 13 such duty cycles at three different current levels is called for in a Standard Operating Duty. The interrupter shown in Fig. 2 executed the equivalent of more than twice the complete ASA Standard Operating Duty requirements, without any adjustment being necessary because of erosion.

This design was chosen for the 560 ampere heavy duty recloser. The interruption rating of this device is 8000 amperes at 15.5 KV and 12,000 amperes at 4.8 KV. Many prototypes have been built and tested significantly beyond the ASA rating, with consistently good performance. Some samples had an arcing duty equivalent to four times the ASA Standard Operating Duty requirements, after which no deterioration in interrupting ability was discernable. The reliability of this device can perhaps best be illustrated by a test in which an arcing current of 45,000 rms amperes, (77,000 amperes peak) was made to flow between the contacts for four cycles. This was considerably above the interrupting ability of this device and the station breaker had to clear the circuit. Immediately afterwards the vacuum interrupter was given the opportunity to clear 9800 amperes at 15.5 KV, which is 20% more than its assigned rating. It did this successfully at the first current zero.

It is known that faults a short distance along a transmission line can tax a circuit breaker severely, because of the sharp initial rise of recovery voltage caused by traveling waves on the line. The recloser-type vacuum interrupter demonstrated very clearly that it could successfully handle this type of fault. The evidence is presented in Fig. 5 which shows a cathode ray oscillogram of the interruption of a 9500 ampere fault at the end of a 0.4 mile transmission line. The first voltage peak is reached at an average rate of 2100 volts/μsec. Line lengths in excess of approximately 0.4 mile would significantly limit the short circuit current at 15.5 KV.

An experimental interrupter of somewhat different design is shown

in Fig. 6. It will be observed that the metallic condensing shield in this model forms part of the vacuum envelope. The glass bushing at each end provides the necessary insulation. The contacts in this device were very similar to those illustrated in Fig. 3. Contact separation was also 1/2".

The interrupting performance of this device was quite remarkable. Altogether, a total of 123 tests were made at voltage levels between 11.5 KV and 25 KV. The maximum asymmetrical current interrupted at 11.5 KV was 54,000 rms amperes. The current in the arc reached 92,000 amperes peak, and arcing lasted for 8 milliseconds. At 15.5 KV, it successfully interrupted, at the first current zero, a symmetrical current of 43,000 amperes. After two successful tests at this level, the current was further increased and the interrupter failed. The arc was sustained four half-cycles before the protective breaker removed the short circuit. It is most noteworthy that after this failure, the interrupter was able to repeat its previous successful high current interruption performance at 15.5 KV and 40,000 amperes. In fact, it later went through over eighty more power tests at different currents and voltages without exhibiting any noticable deterioration. For example, its excellent dielectric strength was demonstrated by its withstanding 110 KV d.c. across the open contact gap, at the conclusion of the interruption tests. One of the tests in which the device cleared 27,000 amperes at 18 KV is particularly deserving of mention because, due to the location of reactors in the circuit, a very high frequency was present in the recovery voltage. The cathode ray oscillogram for this test is shown in Fig. 7. It will be seen that the initial rise of recovery voltage is so fast that it is impossible to assess the rate accurately from an oscillogram where the complete wave shape of the recovery transients over a period of several hundred microseconds is recorded. Other means were therefore employed to measure this quantity. The de-energized test circuit was shock excited by a low step function of current, which evoked an oscillation at the natural frequency of the system, Fig. 8. This was measured and found to be 150 kilocycles/sec., from which it was calculated that the initial rate of rise of recovery voltage in the previous test was 6 KV/μsec. This illustrates, once again, the insensitivity of vacuum interrupters to high recovery rates.

The tests made on this interrupter are summarized in the following table:

Current Range, A	No. of Tests
0-2000	6
2000-5000	64
5000-10,000	15
10,000-20,000	11
20,000-30,000	9
30,000-40,000	8
over 40,000	10

These tests were made over a voltage range of 11.5KV to 25KV. Most of the tests at currents higher than 20,000 amperes were made at 15.5KV. Among the total of 123 tests, there was only one case at 44,000 amperes where the vacuum interrupter did not clear the circuit. Following this the interrupter again successfully cleared 40,000 amperes.

Fig. 9 shows a porcelain clad interrupter which has a slightly smaller envelope but otherwise is very similar to the one just described and illustrated in Fig. 6. The porcelain bushings provided the desired outside creepage path.

Two series of tests were conducted with several of these interrupters. In the first, the performance of individual interrupters was evaluated at 15.5 KV. This permitted another check of consistency. In the second group of tests, two of these interrupters were connected in series and tested at 34.5 KV.

Taking the single interrupter tests first, one of these devices went through a series of 56 power tests. The current level was varied between 10,000 and 66,500 rms amperes, the highest levels being asymmetrical currents. The maximum symmetrical component of the short circuit current cleared at 15.5 KV was 40,000 amperes. One test is singled out for comment because of its remarkable severity. The test circuit would supply a symmetrial current of 41,000 amperes but in this instance the current was asymmetrical, the total rms value being 66,500 amperes, with a peak of 110,000 amperes. The contacts parted shortly after the current was initiated and the total arcing time was 15 milliseconds. The interruption was achieved at the first current zero. The performance of this interrupter was therefore very comparable to that of the interrupter shown in Fig. 6.

A further point of interest was demonstrated by changing the contact gap from 1/2" and 7/8". The maximum currents which could be interrupted at 15.5 KV were the same for both gaps, indicating that in this regard performance of this type of vacuum interrupter is relatively insensitive to gap variation. In addition, transient voltages are not significantly influenced by variations of contact gap or speed of opening.

For the tests with two units in series, capacitors were connected across each break to control the division of the recovery voltage. A total of 28 tests were made at 34.5 KV. The combination successfully interrupted symmetrical currents of 24,000A, and also asymmetrical currents of 32,800 rms amperes with the same available. This does not represent a limit, but only the point at which tests were concluded in order that the interrupters might be used in other experiments.

In summary, it can be justly concluded that it is feasible to interrupt very high currents in vacuum at power system voltages under severe operating conditions. Properly designed, with shields of high condensing efficiency, and with the right contact materials, vacuum interrupters are consistent in performance and capable of a large number of operations with insignificant contact erosion.

PERFORMANCE UNDER MOMENTARY AND CLOSING-IN CONDITIONS

Just as important as the ability to interrupt high currents is the capacity of a circuit breaker to close in on a short circuit, or being closed, to withstand the momentary short circuit current, without contact welding or excessive erosion. At low currents this generally causes no difficulty, but because both the potential weld strength and contact erosion increase sharply with current level, it can become a quite formidable problem at high currents. The situation is even more difficult in the case of vacuum interrupters for two reasons. Firstly, the condition of the electrode surfaces is ideal for welding; there is no surface oxide or other contaminant. One would therefore expect the contact welding problem to be more severe in vacuum than in air, and this is indeed so. The second point, and perhaps this is an even more important one, is that many materials which inherently have good anti-welding properties, such as the refractory metals tungsten and molybdenum, can produce excessive overvoltages due to current chopping and these materials are incapable of good high current interruption performance. On the other hand, a material such as copper, which is good from an interrupting standpoint may form very strong welds when closing in on a short circuit. Here then, is an instance of conflict between two necessary requirements. Of course, one could use one material to close and initiate the flow of current and another material to break it. But this arrangement increases both complexity and cost.

In order to capitalize on the intrinsic simplicity of a vacuum interrupter, a contact material is required which has a combination of desirable properties. These would include good high current interrupting capability, a relatively low chopping level, good dielectric characteristics and satisfactory anti-welding properties. Such a material was not known in the literature or in the industry, but clearly, without it, practical vacuum circuit interruption could not become a reality. It was imperative that an extensive material development program be started for the purpose of developing such a material. This was done and in due course this program was successful. With this special class of material, the contacts can both close-in and withstand momentary short circuit currents without welding and, in addition, their interrupting performance is as good as that of the copper contacts reported in the last section. Closing tests have been made at current levels up to 50,000 amperes. During many tests on 560 ampere recloser interrupters, in which these materials were incorporated, the ASA Standard Operating Duty was performed up to four times on some devices. Frequently, the peak current in closing operations exceeded 30,000 amperes; yet no welding of contacts was ever detected.

Erosion of contacts during closing is often caused by excessive contact bouncing. Under momentary conditions, popping is usually the main cause of erosion. It is known that for a given current level, the erosion rate in air is higher for a very small contact separation, than it is for a large separation[8]. This was also found to be true in vacuum. Thus, popping under momentary conditions should be eliminated and bouncing during closing should be minimized. This can be done by carefully designing the contact structure and properly choosing the contact pressure. By these means long contact life has been realized.

DIELECTRIC PROPERTIES

In common with all other types of interrupters for power circuit applications, the vacuum interrupter must have adequate dielectric strength. It must be able to pass the power frequency high potential tests and the impulse tests specified in industry standards. In the case of the 560A heavy duty recloser, for example, these call for 50 KV at 60 c.p.s. and an impulse withstand of 110 KV for 1.5 x 40 μsec. wave.

In order to design vacuum interrupters to satisfy the standard dielectric tests, basic information on the factors controlling electrical breakdown in vacuum was needed. Unlike breakdown in gases, the fundamental mechanism of vacuum breakdown was not, and indeed, still is not understood. It has often been thought that the breakdown strength of a vacuum gap is high because the mean free path of an electron is so long at these pressures that insufficient ionization of the residual gas by collision occurs, as electrons traverse the space from cathode to anode. In other words, the product of pressure and gap (pd) is far to the left of the so-called Paschen minimum[9]. While this type of reasoning leads to qualitatively reasonable expectations, it does not really explain the basic processes involved, nor does it account for many other well established facts such as the great dependence of breakdown voltage in vacuum on contact material. A trememdous amount of data on vacuum breakdown has been published over the years, some of which appears to be conflicting. Several different theories have been proposed to explain the phenomena observed but the fundamental information needed to prove or disprove the theories is still not available. To design vacuum interrupters in the face of this situation, a very practical approach had to be taken. A series of designed experiments were conducted to determine the effects on dielectric strength of such obviously important factors as contact material, contact geometry, electric field distribution, vacuum seals, and processing. That is to say, the problem was narrowed, as far as possible, to those areas strictly pertinent to a satisfactory engineering solution. This method has proved eminently successful. Information so gathered has been used constantly in the design of practical devices. Typical is the interrupter for the 560 ampere heavy duty recloser which is perfectly capable of meeting the power frequency and impulse requirements.

INSULATION COORDINATION

Vacuum interrupters offer a notable advantage in at least two areas over several traditional types of interrupter. The first concerns the performance of interrupters under multiple lightning stroke conditions. Recently, this problem has attracted much attention[10]. If the first lightning stroke causes a fault on the system which is interrupted by the breaker, its contacts may be in the open position, or part way there, when the second stroke occurs. It is of paramount importance that this second stroke not cause permanent damage to the interrupter as a consequence of arc reignition and ideally, such a reignition should be self-clearing. With many existing interrupters, this is not easy to achieve. But because the current interrupting ability of a vacuum interrupter is relatively insensitive to gap variation, such a reignition is self clearing. The second area concerns evolved faults in which the magnitude of the short circuit current increases abruptly during the opening operation. This can result in damage to an oil interrupter. With a vacuum interrupter, the current will be interrupted at the first current zero without any damage.

ABILITY TO SWITCH LOW INDUCTIVE AND CAPACITIVE CURRENTS WITHOUT PRODUCING ABNORMAL OVERVOLTAGES

The intrinsic high dielectric strength of vacuum and its fast recovery after arcing, make vacuum switches particularly well suited for capacitance switching duties. Many papers report its success in this application[11] and therefore it is unnecessary to discuss this aspect in detail here. When switching small inductive loads, the situation is quite different, for it is well known that vacuum switches are prone to chop when switching low currents. In capacitive or resistive circuits, this is of little consequence, because the surge impedance of the circuit is usually low. But, in inductive circuits, the surge impedance can be quite high, and consequently, there is the possibility of developing abnormal overvoltages. Although this is a well known problem, understanding has been limited. To completely understand the subject, it is necessary to inquire into the behavior of both the interrupter and the circuit. The following questions are relevant:

1) How do the components in a power system respond to a current chop? What is the maximum instantaneous current that can be chopped in a specific application, if the overvoltages generated are to be kept within prescribed limits?

2) Which physical properties of a contact material control the chopping level?

3) Which contact materials have low chopping levels?

A great deal of work had to be done before these questions could be answered. To resolve the first question, a theoretical analysis[12] was made to study the response of transformers and other components in a power system to a current chop. This analysis was confirmed by experimental measurements[13]. Knowledge gained from these studies enabled calculations to be made of the permissible chopping level for any given application.

The second question is very difficult, for it deals with complex phenomena at the arc electrodes. Fortunately, within the authors' company, there have been in the past, many fundamental investigations of the mechanisms prevailing at both the anode and cathode of electric arcs. The results of these investigations have proved to be extremely valuable in providing insights into the events occurring during a current chop. As long ago as 1948[14], current densities at the arc cathode had been studied. Mass transfer or contact erosion and the temperature at the cathode and anode spots were investigated[15]. More recently, the mechanism of electron emission at the cathode[16] has been analyzed in detail, and the cooling effect of electron emission has been studied[17]. This work led to information needed for further study of energy balance at the cathode spot. By applying this accumulated knowledge, it has been possible to determine theoretically the conditions that must be satisfied for a cathode spot to exist, and the current level below which these conditions cannot be met. This level has been related to the chopping level. It was found that the two most important physical properties are the vapor pressure and thermal conductivity of the cathode[18]. This conclusion was in excellent agreement with experimental results which are described in another paper[19].

The third question in the current chopping problem was answered through an extensive program specifically aimed at developing anti-chopping materials. This resulted in the formulation of several classes of material from which contacts can be made in order to eliminate the hazard of overvoltage for any particular application.

The low chopping level of the contact material used in the 560 ampere heavy duty recloser assures its freedom from overvoltage in excess of normal switching surges for any typical application in distribution circuits.

LONG LIFE UNDER BOTH LOAD AND NO LOAD CONDITIONS

As early as 1930, Millikan and Sorensen[20] pointed out that arcing in vacuum has the effect of pumping and that this may reduce the residual gas pressure. If the contact is sufficiently gas-free, every arcing operation will improve the degree of vacuum inside the interrupter, and, there should be no danger of losing vacuum due to arcing alone. This has been confirmed many times with all the experimental interrupters studied in this program. As an example, the vacuum of the device shown in Fig. 6 was very well preserved in spite of being subjected to several times the duty normally expected of a circuit interrupter in its lifetime. Its dielectric strength after this duty is at least as good as it was when new.

In practical applications, however, the interrupter may remain closed for a long period of time; yet, when called upon to perform its protective function, the proper degree of vacuum must prevail. How is good vacuum maintained for prolonged periods without arcing? To answer this, one must look at the mechanisms which can destroy the vacuum inside a sealed device. These are:

1) Permeation of gases through the envelope.

2) Gas evolution from parts inside the envelope.

3) Leaks.

From the permeation point of view, the worst offenders are helium and hydrogen. There is in the atmosphere a partial pressure of 4 microns of helium, while the partial pressure of hydrogen is in general considerably less. Permeation of these gases through the envelope wall can be reduced to an acceptable level by the correct choice of glass and metal for the enclosure, and the correct fabrication of the metal parts. From known information on permeation constants[21] it is possible to design the envelope so that permeation is not a problem in 20 years or more.

To prevent excessive gas evolution from the parts, extreme care must be exercised in selecting materials and in processing. A thorough high temperature bakeout is an essential step in this process.

To preclude leaks as a source of trouble, one must be able to detect leaks so small that, in spite of them, a high vacuum can be maintained for many years. Unfortunately, commercially available leak detectors do not yet have enough sensitivity to insure a life longer than a few months. Consequently, an ultra-sensitive leak detector was developed which is three orders more sensitive than the best commercial instrument. When detecting leaks with the conventional type of leak detector, the sensitivity is normally limited by the lowest partial pressure of the probing gas, which can be measured by the mass spectrometer-amplifier system. Standard practice is to surround the device with a bag of helium. The gas will pass through any leaks and also diffuse through the glass, but the amount of gas involved in the latter process in any reasonable length of time is quite insignificant and is normally below the background of the measuring system. However, this situation frequently does not apply when an ultra high sensitivity mass spectrometer is used in a system with a very small leak, or no leak at all. There is a real problem in differentiating between diffusion and a true leak. Unfortunately, little has been published on the diffusion constants of helium in solids. It was therefore necessary to make measurements to obtain the necessary information. This information was then used in selecting materials for the device and establishing procedures for leak detection.

Another factor to be considered is that, for very small leaks, the leak rate varies with time immediately after the helium is applied[22]. Thus, the process, and therefore the measurement, is a transient one. It was necessary to measure the time constants of the process, for this is another area in which very little is known. During the past two years much valuable information has been gathered and by combining this information with the measured diffusion constants, an ultra-sensitive leak detecting procedure was finally developed.

In developing the leak detecting system, the authors benefited from progress in related technological fields. In particular, the new mass spectrometer tube of Davis and Vanderslice[23] was used in the system.

CONTINUOUS CURRENT CARRYING CAPACITY

Vacuum interrupters differ from conventional devices in many ways as far as the generation and dissipation of heat due to continuous current are concerned. In a vacuum there is no convection so that heat cannot be carried away from the contacts by that means. The only mechanisms are conduction and radiation. Being a sealed device, there is a possibility of generating a large amount of heat due to eddy currents, particularly in ferromagnetic materials. On the other hand, the requirements for temperature rise at the contacts is not as stringent as with air-immersed contacts, because there is no oxygen with which the surfaces can react.

To satisfy this item in the functional specification, analytical studies were made to determine contact drop and the resistive drop in conductors. Other calculations provided data on eddy currents and showed the relation between heat generated and the temperature rise in different locations. By applying these analytical results it was possible to design the 560 ampere heavy duty recloser to ASA temperature limits. It has also been shown that interrupters capable of carrying considerably higher currents are feasible.

OTHER AREAS OF DEVELOPMENT

There are two other areas of special mention. The first concerns materials and processes. Like any other vacuum device the choice of materials and processes determines ultimate success or failure.

At the inception of this program, no commercial equipment was available to perform many of the processing operations which are required in order to fabricate vacuum interrupters. A typical example is vacuum oven equipment. Two large vacuum ovens were therefore constructed for this purpose.

The unique anti-welding materials developed for vacuum interrupter contacts demanded new methods of attachment when it came to joining them to other parts of the device. By their nature, anti-welding materials are difficult to braze and weld. It required much study of the fundamental properties of these materials before means were found to satisfactorily attach the contacts.

Mechanical characteristics of the interrupters also required careful consideration. Unlike electron tubes, vacuum interrupters are subjected to mechanical impact during opening and closing. Stresses set up in this way could adversely affect the glass and the glass-to-metal seals. Difficulties were amplified by the fact that the seals used in the devices reported are much larger than those normally used in electron tubes. Analytical and experimental investigations were made to obtain the necessary design information. At the design stage, every effort was made to relieve the stresses in the glass and the seals, and subsequently each new model was tested under conditions many times more severe than it would encounter in practice.

Among many other areas requiring attention during the development, the following are worthy of special note; the compatibility of materials with their vacuum environment, the matching of coefficients of expansion during temperature cycling and the relief of stress caused by such thermal cycles, the procedures that must be followed to keep all parts clean and free from contaminants.

These problems and many more have had to be solved before bringing the development of vacuum power interrupters to the successful point it has reached to-day.

The second area of development relates to manufacturing facilities. Ultimately, all the techniques and processes evolved for making prototype devices had to be adapted to meet the needs of manufacturing of vacuum interrupters on a commercial basis. This many-sided problem again called for new equipment, many of which had to be completely designed, new methods; and above all a strict quality control program to monitor operations at every stage.

CONCLUSION

For the first time, power vacuum interrupters capable of meeting the functional specifications required by circuit breaker application have been developed. As applied to components and their physical characteristics, these specifications make many demands, some seemingly conflicting. Only by simultaneously satisfying all of these demands has success been achieved.

ACKNOWLEDGEMENT

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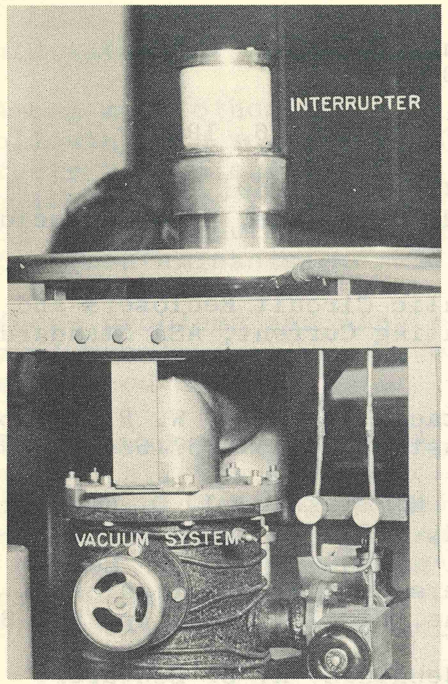

Fig. 1. A continuously pumped vacuum interrupter used to investigate effect of contact materials

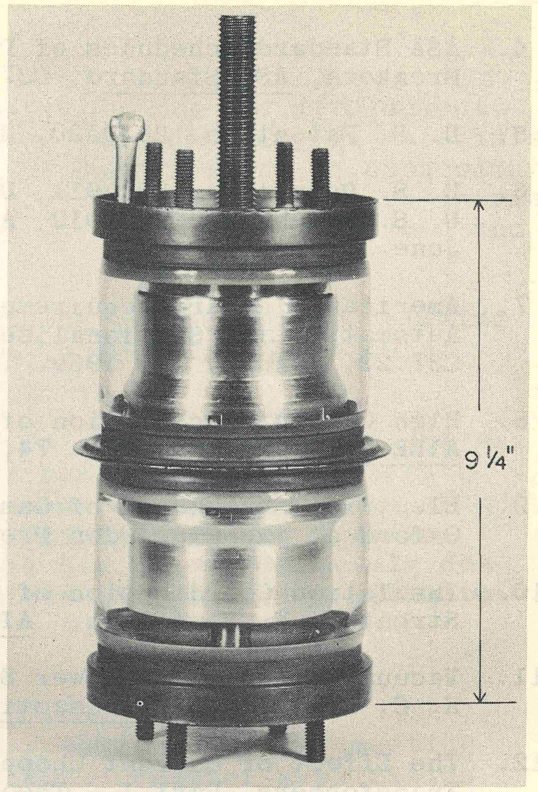

Fig. 2. Experimental prototype for the 560A Heavy Duty Vacuum Recloser

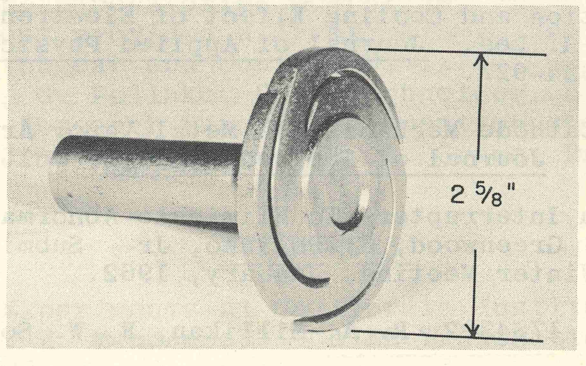

Fig. 3. A spiral-type contact

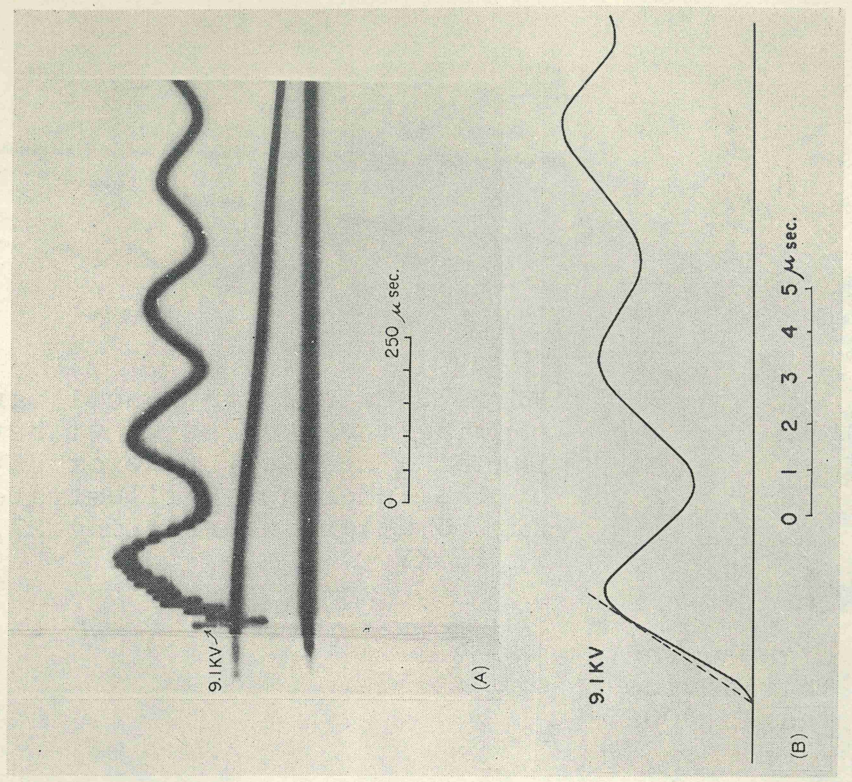

Fig. 5. The clearing by a vacuum interrupter of 9500A fault at the end of a 0.4 mile transmission line.

A) Cathode ray oscillogram

B) Enlargement of the initial period in the recovery voltage transient.

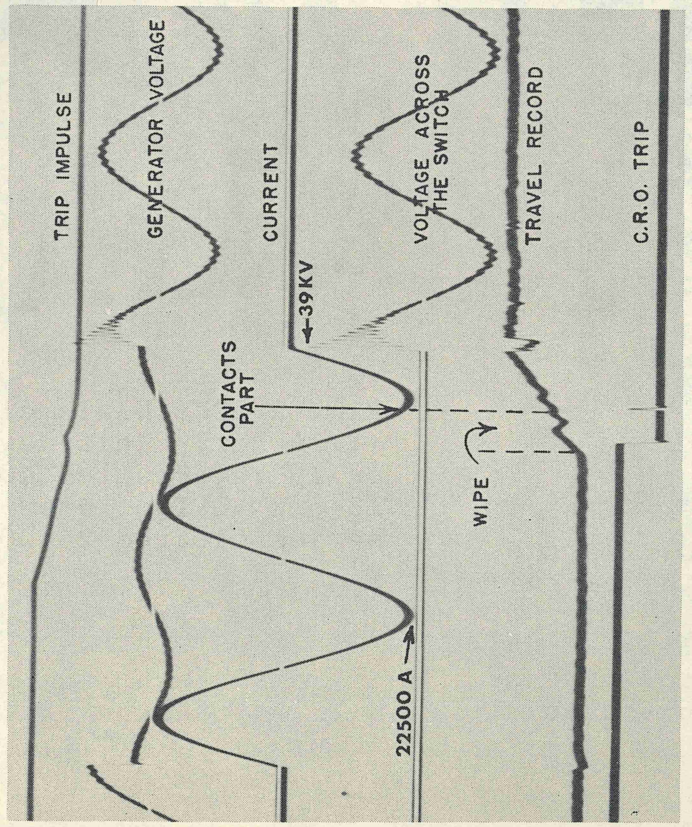

Fig. 4. Oscillogram of a typical interruption test of 14,500A at 15.5 KV performed by a prototype recloser interrupter

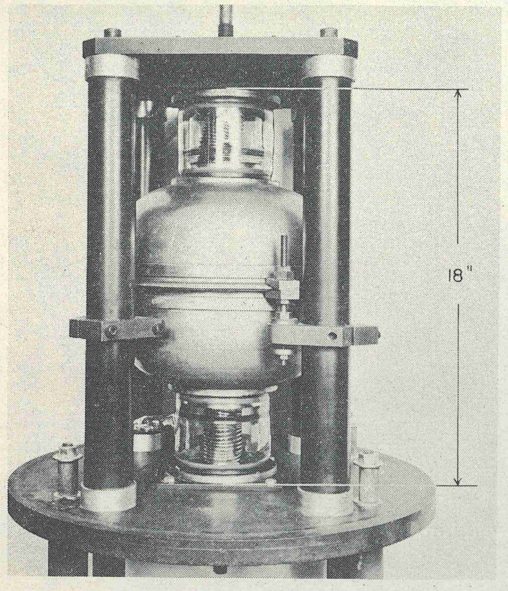

Fig. 6. Experimental high current vacuum interrupter. This device successfully interrupted 43,000A at 15.5 KV

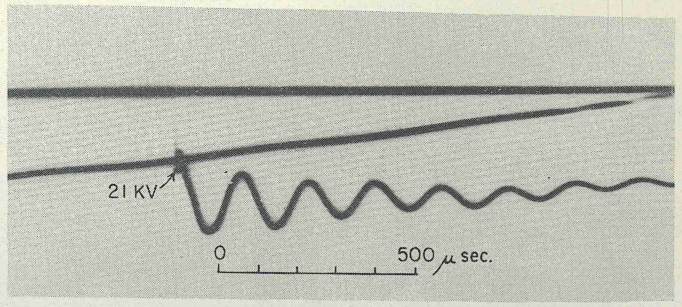

Fig. 7. Cathode ray oscillogram showing the successful withstanding of a recovery rate of 6KV/μsec by the interrupter illustrated in Fig. 3 after interrupting 27,000A at 18 KV.

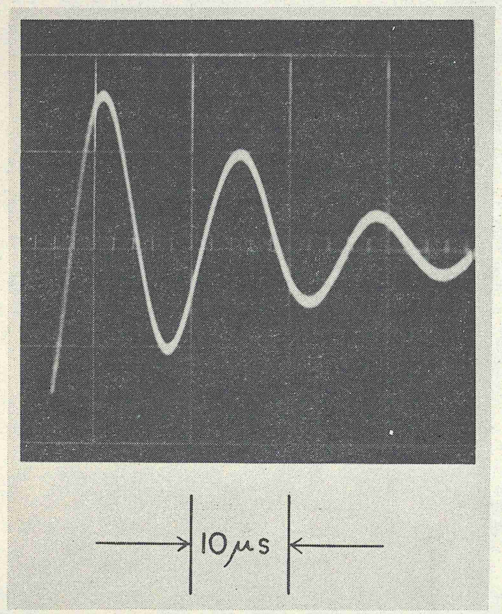

Fig. 8. Oscillogram showing the natural frequency of the circuit for the test recorded in Fig. 8. From this oscillogram it was calculated that the rate of rise of recovery voltage was 6KV/μsec.

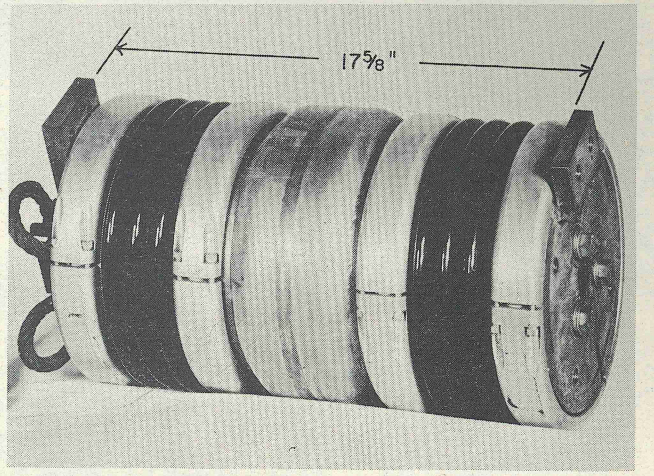

Fig. 9. Porcelain clad vacuum interrupter. This device successfully interrupted 40,000A at 15.5 KV. Two interrupters in series cleared 24,000A at 34.5KV.

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DEVELOPMENT OF POWER VACUUM INTERRUPTERS

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